MULTI-OPTIMIZATION OF PID CONTROLLER PARAMETERS USING STOCHASTIC SEARCH TECHNIQUES FOR ROTARY INVERTED PENDULUM SYSTEM

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To my beloved mother and father

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ABSTRACT

Proportional-Integral-Derivative (PID) controller is a well-known controller in various aspects of industrial automation due to its simplicity and effectiveness in design and implementation of industrial applications. However, it has been difficult to tune up PID controller gains accurately because of complexity and nonlinearity of industrial plants. Therefore, the selection of controller parameters are usually complex and sometimes are selected via trial and error and from designer's intuitive and experience, resulting in less optimal performance. The aim of this project is to analyze and formulate multi-optimization methods for the parameters of the PID controller for controlling the angular displacement of pendulum and arm of Rotational Inverted Pendulum (RIP) system. In this project, the RIP system is chosen due to it is known as an inherent nonlinear system which can be a good prospect for control engineering and MATLAB has been also used to simulate and verify the mathematical model. The performance of the PID controller is evaluated and compared when the parameters are automatically optimized using the Model Reference Adaptive Control (MRAC) concept and stochastic algorithms such as Particle Swarm Optimization (PSO) and Differential Evolution (DE) algorithms for satisfying the main goal which is balancing the pendulum in the vertical position. Finally, the results demonstrated the robustness and effectiveness of the designed PID controller by proposed stochastic algorithms in terms of easy implementation, computational cost, complexity and effectiveness. As a conclusion, these proposed stochastic search techniques can be considered as systematic and effective ways to control the various nonlinear industrial plants.

ABSTRAK

Pengawal Berkadar-Kamiran-Terbitan (PID) sangat terkenal dalam pelbagai aspek industri automasi kerana kesederhanaan dan keberkesanan rekabentuk dan pelaksanaannya dalam aplikasi industri.tersebut. Walaubagaimanapun, adalah sukar untuk melaraskan gandaan pengawal PID ini secara tepat kerana ia melibatkan proses yang komplek dan tidak linear dalam sesuatu proses industri . Oleh itu, pemilihan parameter pengawal biasanya lebih komplek dan kadangkala dipilih melalui kaedah cuba jaya dan berdasarkan kepada pengalaman serta kebolehan pereka itu sendiri, yang mengakibatkan prestasi pengawal kurang optimum. Oleh sebab itu, projek ini membentangkan analisis dan perumusan kaedah pelbagai pengoptimuman dengan mencadangkan parameter pengawal PID untuk mengawal anjakan sudut bandul dan lengan putaran bagi sistem bandul songsang (RIP). Pemilihan model ini adalah kerana sistem ini dikenali sebagai satu sistem yang wujud secara tidak linear yang boleh menjadi prospek yang baik dalam mengkaji system kejuruteraan kawalan. Perisian MATLAB telah digunakan untuk proses simulasi dan pegesahan model matematik yang di gunakan. Pengawal PID bagi model ini akan direkabentuk menggunakan kaedah Adaptive Kawalan Model Rujukan (MRAC) dan kemudian keputusannya akan dianalisa. Model yang serupa akan direka semula menggunakan kaedah stokastik iaitu “Particle Swarm Optimization (PSO)” dan kaedah Berbeza Evolusi (DE) untuk mengoptimumkan indeks prestasi dalam usaha untuk melaraskan pengawal PID bagi memenuhi matlamat utama mengimbangi bandul dalam kedudukan menegak. Akhirnya, keputusan simulasi menunjukkan keteguhan dan keberkesanan pengawal PID yang direka menggunakan teknik-teknik pintar ini dari segi pelaksanaan yang mudah, kos pengiraan, kerumitan dan keberkesanan. Oleh itu, teknik carian stokastik ini boleh dianggap sebagai cara yang berpotensi untuk mengawal proses tak linear dalam industri.

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LIST OF ABBREVIATIONS

DC	-	Direct current
PID	-	Proportional Integral Derivative
MATLAB	-	Matrix Laboratory Software
MRAC	-	Model Reference Adaptive Control
PWM	-	Pulse Width Modulator
IAE	-	Integral absolute error
ITAE	-	Integral Time Absolute error
ISE	-	Integral Square Error
ITSE	-	Integral Time Square Error
PSO	-	Particle Swarm Optimization
DE	-	Differential Evolution
RIP	-	Rotational Inverted Pendulum

LIST OF SYMBOL

L_1	-	Length of actuating link
L_2	-	Length of pendulum link
I_0	-	DC motor inertia
M_1	-	Mass of actuating motor
M_2	-	Mass of pendulum link
J_1	-	Inertia of actuating link
J_2	-	Pendulum link Inertia
G	-	Gravity coefficient
C_1	-	Distance to center of gravity of pendulum link
C_2	-	Distance to center of gravity of actuating link
R_a	-	DC motor armature resistance
K_r	-	Torque transmission coefficient
K_b	-	Back-EMF coefficient
θ_1	-	Angular displacement of actuating link (arm)
$\dot{\theta}_1$	-	Angular velocity of actuating link (arm)
θ_2	-	Angular displacement of pendulum link
$\dot{\theta}_2$	-	Angular velocity of pendulum Link

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CHAPTER 1

INTRODUCTION

1.1 Introduction

This chapter covers the Rotational Inverted Pendulum system (RIP), Proportional-Integral-Derivative (PID) controller, Model Reference Adaptive System (MRAS), Particle Swarm Optimization (PSO), Constriction Coefficient method of PSO algorithm (CPSO) and Differential Evolution (DE) algorithm. The motivation of applying PSO, CPSO and DE as an optimization algorithms is also considered in this chapter.

1.2 Overview

During the past decades, numerous modern control methodologies have been introduced and applied for control approaches and industrial application [1-2] such as nonlinear control [2-3], Linear Quadratic regulator [3-4], optimal control [5], Pole placement controller [6] and adaptive control combined with state feedback controller [5-7-9].

However, these methods are complex in theory and difficult to implement especially in industrial plants [1]. PID controller is high well-known method for industrial control procedures [6, 7]. This approach has been broadly employed in wide ranges of industries [8] because of its simple structure and robust performance

[8-10-12]. Unfortunately, it has been difficult to tune up PID parameters accurately because of complexity of many industrial plants such as higher order, time delays, and nonlinearities [7, 9].

Ziegler and Nichols presented the simple method that is widespread as classical tuning rules [10]. Though, the determination of optimal PID controller parameters with Ziegler-Nichols formula [14] results in less optimal performance [9-10].

To overcome these difficulties, over the past years, several evolutionary algorithms have been proposed to search for optimal PID controllers. In this project, the efficiency of two intelligent algorithms is compared, that are DE and PSO. These evolutionary algorithms are used to adjust the PID controller parameters [5] of the closed-loop system of RIP. For this purpose, the model proposed is Rotational Inverted Pendulum (RIP) system. The reason to choose this model is that this system is known as inherent nonlinear system which can be a good prospect for control engineering.

1.3 Rotational Inverted Pendulum

Rotary Inverted Pendulum system as shown in Figure 1.1 is a challenging problem in the area of control systems and this system is inherently unstable and nonlinear system [22]. It is a familiar system chosen for evaluation various control techniques [23],[15]. It has also some significant real life applications such as pointing control, aerospace vehicle control[19], robotics[1, 18, 19], control professionals[22],pendulum rides[24, 25], crane machine, rockets[19], robotic arm[1, 11,18], the flight simulation of rocket or missile[18] and other transportation means[2] and etc. Some example of real life applications of RIP system are shown in figure 1.2 and 1.3. Besides that, RIP is widely used as benchmark for testing control algorithms such as Proportional Integral Derivative (PID) controllers, neural networks, and fuzzy control. The reasons for selecting the Inverted Pendulum system as the tester bed for the controller design are because the system is a nonlinear system and easily available for laboratory usage. Another advantage is it can be treated as a linear system without much error compared to nonlinear model for a wide range of variation [2-18].

Figure 1.1: Rotary Inverted Pendulum model [18]

Figure 1.2: Pendulum rides

Figure 1.3: Crane machine

1.3.1 Description of Rotational Inverted Pendulum System

The rotary inverted pendulum consists of a rigid rod (pendulum) rotating in a vertical plane. The rigid rod is attached to an actuating link (arm) that is fixed on the shaft of the servo motor. The actuating link (arm) can be rotated horizontally by the servo motor, while the pendulum hangs downwards. A normal pendulum is considered stable when hanging downwards, while the rotary inverted pendulum is inherently unstable, and must be actively balanced for remaining upright, either by utilizing a torque at the pivot arm or by moving the pivot arm horizontally as part of a feedback system. A diagram of the RIP system is shown in Figure 1.4, where L_1, L_2, M_1, M_2, θ_1, θ_2 are the length of arm, the pendulum length, the arm's mass, the pendulum's mass, the angular displacement of arm and the angular displacement of pendulum, respectively. The input of RIP system in this research is considered the torque of motor and the performance of angular displacement of pendulum and angular displacement of arm will be analyzed separately as the output of RIP system.

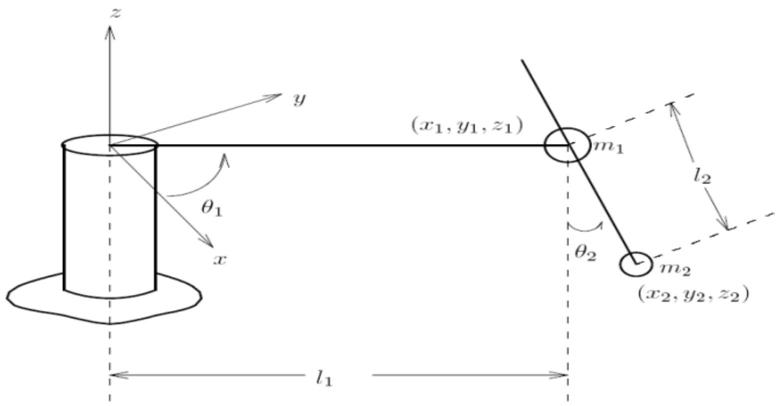

Figure 1.4: Diagram of Rotary Inverted Pendulum

1.4 PID controller

A proportional–integral–derivative controller (PID controller) is the most common form of feedback controllers and widely is used in industrial control systems (see Fig 1.5). A PID controller calculates an "error" value as the difference between a desired set-point and a measured process variable. The controller signal (u) attempts to minimize the error by adjusting the process inputs as follow:

$$u = K_P e(t) + K_I \int e(t)dt + K_D \frac{de}{dt} \tag{1.1}$$

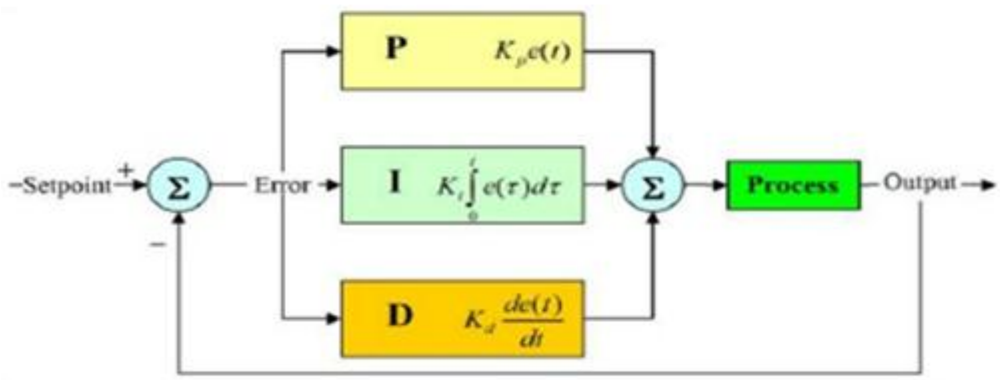

Figure 1.5: Block Diagram of PID controller

1.4.1 The characteristic of P, I and D controllers

The transfer function of PID controller looks like the following:

$$\boldsymbol{K_P} + \frac{\boldsymbol{K_I}}{\boldsymbol{s}} + \boldsymbol{K_D}\mathrm{s} = \frac{\boldsymbol{K_D s^2 + K_P s + K_I}}{\boldsymbol{s}} \tag{1.2}$$

- K_P = Proportional gain
- K_I = Integral gain
- K_D = Derivative gain

A proportional gain (K_P) will have the effect of reducing the rise time and will reduce the steady steady-state error, but never eliminate, the steady-state error. An integral gain (K_I) will have the effect of eliminating the steady-state error, but it may make the transient response worse.

A derivative gain (K_D) will have the effect of increasing the stability of the system, reducing the overshoot, and improving the transient response. Effects of each of gains K_p ,K_D, and K_I on a closed-loop system are summarized in the table shown below.

Table 1.1: Effect of PID gains on a closed-loop system [7]

Parameter	Rise Time	Overshoot	Setting Time	Steady State Error
$\boldsymbol{K_p}$	Decrease	Increase	Small change	Decrease
$\boldsymbol{K_I}$	Decrease	Increase	Increase	Eliminate
$\boldsymbol{K_D}$	Decrease	Decrease	Decrease	Slight change

Note that these correlations may not be exactly accurate, because K_p, K_i, and K_D are dependent of each other. In fact, the table should only be used as a reference when you are determining the values for K_i, K_p and K_D.

1.5 Model Reference Adaptive System

Adaptive system is defined by (Narendra and Annaswamy,1989) [5] as a system which is provided with a means of continuously monitoring its own performance in relation to a given figure of merit or optimal condition and a means of modifying its own parameters by a closed loop action to approach a optimum condition. MRAS that uses Model Reference Adaptive Control (MRAC) is an adaptive system that makes overt use of such models for identification or control purposes. MRAC as adaptive controller is chosen to control the RIP system based on the performance wise and other characteristics. Tracing back chronologically from 1950s [5,7] until now, the automatic control of physical processes has been an experimental technique deriving more from art than from scientific bases. When implementing a high-performance control system, the poor characteristic plant dynamic characteristics starts to arise. Besides that large and unpredictable variations occur. As a result, a new class of control systems called adaptive control systems has evolved which provides potential solutions. In the late 1950s, many solutions have been proposed in order to make a control system “adaptive” and among of them is a special class of adaptive systems called Model Reference Adaptive System.

1.6 Evolutionary & Stochastic Algorithms

Evolutionary Algorithms (EAs) are computer-based problem solving systems. They use computational models of evolution mechanism in their design and implementation. The idea behind evolutionary algorithm is to imitate the natural evolution to solve optimization problems. A relationship between evolution of the nature and optimization of design is established in order to find the optimum.

Evolutionary Algorithms simulate the evolution of individual structures via processes of selection, mutation and recombination.

Stochastic optimization plays a significant role in the analysis, design, and operation of modern systems. Methods for stochastic optimization provides a meant of coping with inherent system noise and coping with models or systems that are highly nonlinear, high dimensional, or otherwise inappropriate for classical deterministic methods of optimization. Algorithms that employ some form of stochastic optimization have been widely available as stochastic optimization algorithms and have broad application to problems in statistics, science, engineering, and business.

1.6.1 Particle Swarm Optimization Algorithm

PSO as popular optimization technique representatives of stochastic algorithms was introduced in 1997 by Eberhart and Kennedy [13]. PSO algorithm is considered as swarm intelligent algorithm because of self-organization and information communication between its particles and it is also a meta-heuristic algorithm because with few information of optimization problem is able to solve the problems. It is also applied to serves PID controller on plant associated with nonlinearities. The PSO algorithm is initialized with a population of random particles (birds). These particles have two essential capabilities: their memory of their own best position and knowledge of the global best. Members of a swarm communicate good positions to each other and adjust their own position and velocity based on good positions.

In this project, the search space is a three-dimensional axes that are K_P, K_I and K_D axes. Then the position, velocity of ith particle and how they can be updated of nth iteration it could be represented as follow. The new position and velocity determined by the basic PSO formula as follow:

$x_i = (x_{iP}, x_{iI}, x_{iD}) = (K_P, K_I, K_D)$ and $V_i = (V_{iP}, V_{iI}, V_{iD})$

$$v(k+1)_{i,j} = w.v(k)_{i,j} + c_1r_1(gbest - x(k)_{i,j}) + c_2r_2\,(pbest_j - x(k)_{i,j}) \quad (1.3)$$

$$x(k+1)_{i,j} = = x(k)_{i,j} + v(k)_{i,j} \quad (1.4)$$

Where

$v_{i,j}$ velocity of particle i and dimension j

$x_{i,j}$ position of particle i and dimension j

C_1, C_2 Learning factors and represent the cognition and social components, respectively, which attract the particles to the local best and global best positions.

w Inertia weight factor

r_1, r_2 Random numbers between 0 and 1

pbest Best position of a specific particle

gbest Best particle of the group

1.6.1.1 Constriction Coefficient of PSO

In order to more exploit local and global exploration in 2002, Clerc and Kennedy proposed an adaptive PSO model called CPSO method [35-47] that uses a new parameter ‘χ’ called the constriction factor. The model also excluded the inertia weight ω and the maximum velocity parameter V_{max}. The velocity update scheme proposed by Clerc can be expressed for the dth dimension of ith particle as:

$$V_{id}(t+1) = \chi\,[V_{id}(t) + C_1.\varphi_1.\big(P_{id}(t) - X_{id}(t)\big) + C_2.\ \varphi_2.(g_{id}(t) - X_{id}(t))]$$

$$X_{id}(t+1) = X_{id}(t) + V_{id}(t+1) \tag{1.5}$$

Where,

$$\chi = \frac{2}{|4-\varphi-\sqrt{\varphi^2-4\varphi}|} \text{ with } \varphi = C_1 + C_2 \tag{1.6}$$

In order to initialize the parameters of PSO algorithm, CPSO method proposed a specific range for Inertia weight factor (w) and acceleration factors (C_1, C_2) of PSO algorithm as follow:

$$\emptyset_1, \emptyset_2 > 0 \quad \text{Where} \quad \emptyset \triangleq \emptyset_1 + \emptyset_2 > 4 \tag{1.7}$$

$$\text{Constriction coefficient Factor} = \chi = \frac{2}{|4-\varphi-\sqrt{\varphi^2-4\varphi}|} \tag{1.8}$$

Where

$$w = \chi \quad , \quad C_1 = \chi.\phi_1 \text{ and } C_2 = \chi.\phi_2 \tag{1.9}$$

1.6.2 Differential Evolution Algorithm

Another optimization technique, which has emerged in 1995 is DE algorithm introduced by Price and Storn that it is a population based algorithm like genetic algorithms using the similar operators; crossover, mutation and selection. The main difference in constructing better solutions is that genetic algorithms rely on crossover while DE relies on mutation operation. This main operation is based on the differences of randomly sampled pairs of solutions in the population.

The algorithm uses mutation operation as a search mechanism and selection operation to direct the search toward the prospective regions in the search space. The DE algorithm also uses a non-uniform crossover that can take more information to search for a better solution space.

The DE algorithm serves PID controller on nonlinear plant as task consisting of three parameters can be represented by a 3-dimensional vector. In DE, a population of NP solution vectors is randomly created at the start. This population is successfully improved by applying mutation, crossover and selection operators.

1.6.2.1 Mutation

For each target vector, a mutant vector is produced by

$$v_{i,G} = x_{i,G} + K.\left(x_{r1,G} - x_{i,G}\right) + F.\left(x_{r2,G} - x_{r3,G}\right) \tag{1.10}$$

Where I,,, (1,2,……,NP) are randomly chosen and must be different from each other. In equation (1.11) F is the scaling factor which has an effect on the difference vector, K is the combination factor.

1.6.2.2 Crossover

The parent vector is mixed with the mutated vector to produce a trial vector

$$u_{ji,G+1} \begin{cases} v_{ji,G+1} & if \ (rndj \leq CR) or \ j = rni, \\ q_{ji,G} & if \ (rndj > CR) and \ j \neq rni \end{cases} \tag{1.11}$$

Where j=1,2,…..,D; $r_j \in [0,1]$ is the random number; CR is crossover constant $\in [0,1]$ and r$r_{ni} \in (1,2,\ldots,D)$ is the randomly chosen index.

1.6.2.3 Selection

All solutions in the population have the equivalent chance of being selected as parents without dependence of their fitness value. The child produced after the mutation and crossover operations is evaluated. Then, the performance of the child vector and its parent is compared and the better one is selected. If the parent is still better, it is improved in the population.

$$X_{i,G+1} = \begin{cases} u_{i,G+1} & if\ f(u_{i,G+1}) < f(X_{i,G})\ for\ minimization\ problems \\ X_{i,G}, & otherwise \end{cases} \quad (1.12)$$

1.7 The Importance of the study

The open loop rotary inverted pendulum is an inherent unstable system. The controller design shall improve the transient response, steady state error and stability of system. This research mainly converts the uncompensated system to the compensated system. Then, it is to ensure whether the design of the PSO-PID and DE-PID controllers meet the desired output or not.

1.8 Problem identification/statement

(i) Rotary inverted Pendulum is inherently unstable system, which moves continually toward an uncontrolled state.

(ii) The problem of designing PID controllers as an optimization problem which tuning value of K_P, K_I and K_D are very complicated and conventional tuning may result poor performance specially for controlling a non-linear processes . The suggestion is trying to solve with PSO & DE for better system's performance.

1.9 Objectives of project

(i) To apply Lagrange's equation in order to obtain mathematical model of the rotary inverted pendulum system.

(ii) To tune of PID parameters automatically for RIP based on MRAC concept.

(iii) To tune PID controller parameters that is applied to RIP by utilizing stochastic algorithms such as PSO and DE algorithms.

(iv) To compare the performance of PID controller with proposed evolutionary approaches, which it is desired that these stochastic optimization algorithms to achieve superior quality of solution and performance.

1.10 Scope of project

For this work at the following steps should be done

(i) Achieving the nonlinear model of RIP system by using Lagrange method.

(ii) The project proposes standard PSO and DE algorithms and MRAC controller to tune the PID parameters.

(iii) Off-line tuning of PID gain to the RIP system by simulation.

(iv) Only control angular displacement of Pendulum and actuating link (arm) of RIP system.

(v) Enhancing the performance of RIP system by minimizing the overshoot, rise time, setting time and steady state.

1.11 Summary of Chapter

This chapter explains in general about the RIP system, PID controller, adaptive controller, PSO and DE algorithms. The subsequent point is some outline of this project and expresses the major objective to attain. Eventually the scope of the project releases some goal of this project.

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